CATASTROPHIC IMPACTS AND ASTEROID ROTATION RATES. S. G. Love and T. J. Ahrens, Seismological Laboratory 252-21, California Institute of Technology, Pasadena CA 91125.

Asteroid rotation [1] is controlled by mutual impacts [2-8]. Asteroid spin and collisional history have traditionally been linked by analogy to experimental impacts on cm-scale targets cohering by material strength [2, 3, 9-11]. Recent work, however, questions that analogy for objects the size of most observed asteroids (> 1 km in diameter), where gravity rather than strength controls impact response [12-14]. Here we discuss computer models of impacts on gravitating bodies which explain some observed rotational properties of asteroids.

The computer model [14], a 3-D Smoothed Particle Hydrodynamics (SPH) code, neglects intrinsic strength (justifiable for the targets treated here [12-14]) but treats gravity rigorously. We explicitly compute the projectile's contact with the target, compression at the impact site, ejecta launch, and propagation of the impact shock wave to the target antipode on a time scale of seconds to minutes. Later evolution of the system is primarily ballistic and is treated analytically.

In the ballistic phase, we find the kinetic energy (K) of each of the ~2000 mass elements along with the energy of gravitational binding (W) between each particle and all the other particles in the system. Particles with $K<|W|$ do not escape; these form the final "rubble pile." We calculate the rubble pile's angular momentum and spin rate neglecting gravitational torques between it and the escaping ejecta and assuming that the bound particles reaccrete into a homogeneous sphere. The results, including the final-to-initial target mass ratio, μ, for typical trials, are summarized in Table 1.

Applying these results to observed asteroid spin rates is uncertain because we treat only a single impact rather than the sum of many. Nonetheless, combining the present rotation results with the observation that target mass removal is proportional to impactor mass for a given target diameter [14] and including an impactor mass distribution (with a power law slope near -1.7 [5, 9]) allows us to compare the importance of different sized impacts in controlling asteroid spin (Fig. 1). Small erosive events are frequent but have little effect on the spin. Impacts leaving less than ~0.25 of the target's mass alter rotation significantly, but not enough to compensate for their rarity. Between those extrema, occasional catastrophic impacts leaving remnants with μ = 0.40 to 0.65 are the most effective in changing asteroid rotation rates. According to the present model, such impacts produce (on initially nonrotating targets) spin rates of 1.8-4.2 day^{-1}, consistent with the ~2.5 day^{-1} observed asteroidal mean rotation rate [2, 4]. Impact ejecta trajectories in this model are mainly downrange, so we cannot directly compare the present results with "angular momentum drain" [6] or "angular momentum splash" [3], which are based on axisymmetric launch of ejecta from asteroid impact sites.

Our results show that final spin rate is related to the fraction of retained target mass and the impact angle, but not absolute target diameter or impact speed in the ranges investigated. Grazing (75°) impacts yield spin rates ~2x those at 45° for the same degree of mass loss; near-vertical (15°) impacts produce spin frequencies a factor of ~ 2 smaller. The absence of a strong size effect contrasts with the notion that a change in collision physics might be responsible for the excess of slowly rotating asteroids of diameter near 100 km [2, 4]. Instead, we suggest that this effect arises from a change in the composition or differentiation of asteroids at that diameter, or from a change in the population of projectile asteroids at the size appropriate to drastically alter the spin of 100 km targets.

For a sphere, the breakup spin rate is given by $f_{max} = (G\rho/3\pi)^{0.5}$, where ρ and G are the density and the gravitational constant. For increasingly large impacts, we find final spin rates that approach but do not reach the breakup limit. This effect suggests that density may influence spin rate [7, 15]. In fact, the observed mean spin frequencies of C, S, and M class asteroids (2.2 day^{-1}, 2.5 day^{-1}, and 4.0 day^{-1} respectively [4]) fall in nearly the same proportion as the square roots of their presumable densities (~2000, ~2700, and ~7800 kg m^{-3}). We have investigated the relationship between spin and density in our model. Two simulations using iron (ρ = 7800 kg m^{-3}) targets showed spin rates ~1.9 times faster than for granite with the same mass loss, consistent (within scatter) with $\rho^{0.5}$ scaling which predicts a factor of 1.7. Analogously, two runs using dry tuff (ρ = 1700 kg m^{-3}) yielded spin rates averaging 0.8 times that of granite, also consistent with $\rho^{0.5}$ scaling. We suggest on the basis of this favorable agreement that the observed trend in rotation rate from C to S to M class asteroids arises from increasing density [7, 15], and predict that collisionally mature Kuiper Belt objects (ρ ~ 1000 kg m^{-3}) should have a mean spin rate near 1.5 day^{-1}.

Finally, Table 1 shows each rubble pile's angular momentum expressed as a fraction (ζ) of that initially carried by the projectile. The ζ parameter is important in asteroid spin evolution models [2, 6-8]. Experimental values of ζ are 0.1 to 0.7 [10, 11]. We find that ζ ranges from 0.01 to 0.1. Assuming a constant value of ζ thus appears problematic for spin evolution models. Furthermore, ζ in large asteroid collisions seems to be significantly smaller than observed in cm-scale laboratory impacts.

TABLE 1. TYPICAL MODEL OUTCOMES

Initial Target Diam. (km)	Target Remnant Mass ratio, μ	Spin rate (day^{-1})	L/L_{proj}, ζ
10.0	0.54	2.38	0.062
31.6	0.88	0.248	0.046
100.	0.69	1.19	0.068
100.	0.38	4.11	0.043
100. •	0.61	3.74	0.064
100. ••	0.53	1.62	0.060
316 *	0.89	0.311	0.037
316 †	0.51	1.19	0.091
316	0.72	1.16	0.058
316	0.89	0.764	0.040
316 §	0.46	2.73	0.045
316 §	0.74	1.74	0.048
316	0.52	3.82	0.066
1000	0.58	4.02	0.066

Nominal case is impact at 45° and 5 km/s, with granite projectile and target. *3 km/s. †15°. 75°. §7 km/s. •Iron projectile and target. ••Dry tuff projectile and target.

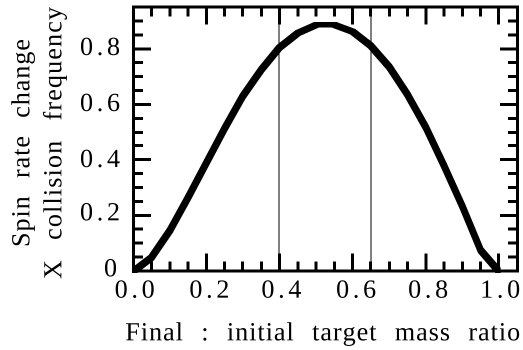

FIGURE 1: Relative importance (in arbitrary units) of impacts of different severity in determining asteroid rotation rate. Shown is the product of the change in asteroid spin rate imparted by impacts of various sizes (from the present model) and the relative frequency of such collisions (assuming a projectile mass-frequency with a power-law slope of -1.7). Collisions leaving target remnants with 0.40 to 0.65 of their original mass, corresponding to a change in spin rate of 1.8-4.2 day^{-1}, contol rotation rate evolution.

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